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On time variability and other complications in studying the UV broad absorption lines of quasars: results from numerical simulations of radiation driven disk winds.

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Abstract. We review the main results from axisymmetric, time-dependent hydrodynamical simulations of radiation driven disk winds in AGN. We illustrate the capability of such simulations to provide useful insights into the three domains of observational astronomy: spectroscopy, time-variability, and imaging. Specifically, the synthetic line profiles predicted by the simulations resemble the broad absorption lines observed in quasars. The intrinsically time dependent nature of radiation driven disk winds that have been predicted by the simulations can be supported by a growing number of the observed dramatic variability in the UV absorption lines. And finally, the intensity maps predicted by the simulations give physical and geometrical justification to the phenomenologically deduced fact that a proper interpretation of the observed line absorption requires the wind covering factor to be considered as being partial, inhomogeneous, and velocity dependent.

1. Introduction

AGN are powerful sources of both electromagnetic radiation and mass outflows. Broad absorption lines (BALs) in quasars are the most dramatic evidence of the mass outflows.

Although quasars were discovered 50 years ago, only now are we starting to gain observational insight into the BAL time-variability on various time scales by monitoring relatively small samples of objects (e.g., Barlow 1994; Lundren et al. 2007; Gibson et al. 2008, 2010; Capellupo et al. 2011). The variability of AGN outflows can be very dramatic. In particular, it could be manifested as emergence of BALs in UV spectra of quasars (e.g., Hamann et al. 2008; Krongold et al. 2010; Hall et al. 2011) and even in a Seyfert 1 galaxy Leighly et al. (2009). The time-variability provides new constraints for the outflow physics and geometry. The prospects of studying the time variability of BALs are very good considering the success of recent observational campaigns (see Brandt and Haggard in this volume). For example, spectra of 150,000 quasars from the Baryon Oscillation Spectroscopic Survey (BOSS) of SDSS-III are ex-

pected to increase the number of known quasars with multi-year variability in BALs by two orders of magnitude, offering a sample of up to 2000 objects instead of 20.

Disk accretion onto a massive black hole (BH) is most likely a source of the powerful radiation. Therefore, it is very plausible that the BAL outflows originate from the accretion disks and are driven by the same powerful radiation (e.g., reviews by König 2006). We argue that disk winds are a crucial ingredient of disks and can help us understand the entire disk accreting system. In particular, if broad emission lines, one of the defining features of quasars, are associated with disk winds (e.g., Richards et al. 2011), then a physical model of the latter will be a very important element of understanding reverberation-mapping measurements used to estimate BH masses, one of the fundamental parameters of AGN. In addition, as mass outflows propagate outward, they can significantly affect the medium they interact with. Therefore, the outflows should be one of the key processes in the so-called AGN feedback (see, Ostriker and other contributions in this volume).

2. Simulations

Disk winds are inferred to exist in many, if not even all disk accreting systems. Therefore, there is an extensive literature on disk wind studies where various approaches – such as analytic and semi-analytical models and numerical simulations – were adopted. The problem is quite complex due to non-spherical geometry and the richness of the physical processes operating in the disk and wind. Therefore, the level of completeness and self-consistency varies from model to model.

We have been involved in several numerical studies of radiation driven disk winds. In particular, in Proga et al. (2000) and Proga & Kallman (2004), we presented results from axisymmetric, time-dependent simulations of an accretion disk wind driven by radiation pressure on spectral lines. The simulation, described in greatest detail in Proga & Kallman (2004), is for a nonrotating BH with a mass of $10^8 M_\odot$ and an accretion luminosity of 50% of the Eddington luminosity. It followed three flow components: (i) a hot and low density inflowing gas in the polar region, (ii) a dense, warm and fast *equatorial* outflow from the disk, and (iii) a transitional zone in which the disk outflow is hot and struggles to escape the system. The third component shields the disk wind (the second component) from powerful ionizing radiation produced by the central engine so that radiation pressure on spectral lines can launch and accelerate the wind. One of the predictions of the radiation-driven disk wind simulations is that the wind is intrinsically time-dependent: the wind solution is unsteady even though the base of the wind and the driving radiation are assumed to be time independent. The left panels of Figure 1 illustrate the overall wind structure and time variability.

The simulations of radiation-driven disk winds succeeded in producing a fast wind that is capable of accounting for BAL winds and other winds. Thus they can be considered a “proof-of-concept” for a radiation driven disk wind in AGN.

To gain more insights into how these simulations compare with observations, synthetic line profiles and broad band spectra have been calculated based on the simulations. The synthetic line profiles show a strong dependence on inclination angle: the absorption forms only when an observer looks at the source through the fast wind (i.e., $i \geq 60^\circ$; see fig. 2 in Proga & Kurosawa (2009)). This i -dependence could explain why only 15% of quasars have BALs: it may simply be a selection effect of viewing angle. The model also predicts high column densities and subsequently strong X-ray

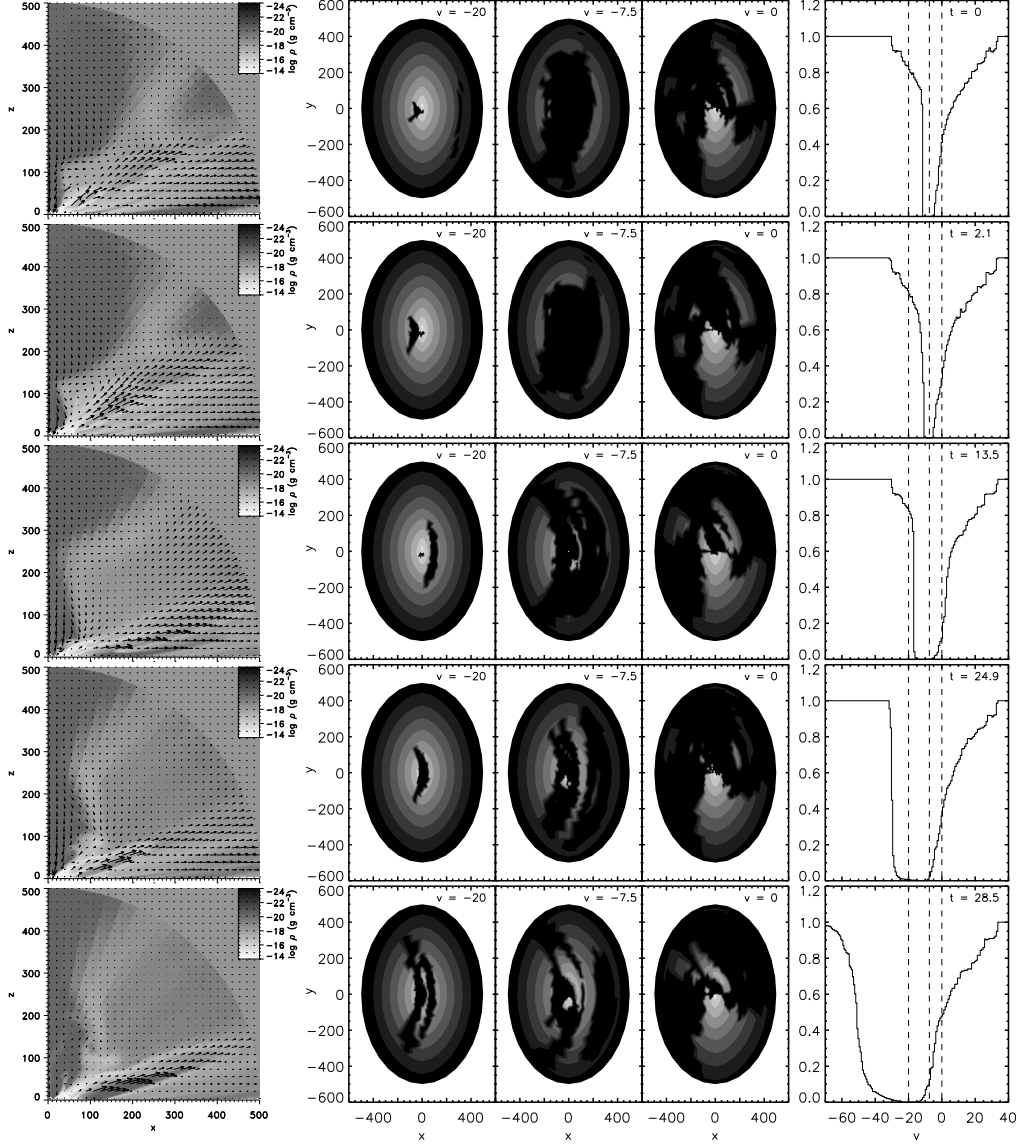


Figure 1. A time sequence of density and velocity maps (left column), intensity maps (second, third, and fourth columns) and of absorption line profiles (right column). The time (the labels in the top right corner of the right panels) is measured in months with respect to the time of the first snapshot that has been described in detail in Proga & Kallman (2004). In the density and velocity maps, the rotation axis of the disk is along the z -axis, while the midplane of the disk is along the x -axis. The position on the maps is expressed in units of the disk inner radius r_* which corresponds to 3 Schwarzschild radii (the inner radius of the computational domain is $10 r_*$). The profiles and maps of the disk intensity as viewed through a disk wind are computed for the C IV 1549 Å line and an inclination angle of 75° (the angle is measured from the rotational axis). Hence the disk in the intensity maps is flattened and the near and far side of the disk are, respectively for positive and negative values of the x -coordinate. The maps are plotted using a logarithmic scale with ten levels each spanning 2 orders of magnitude. The three columns with intensity maps correspond to three velocities (see the labels in the top right corner of the maps). The three velocities are also marked by the dashed vertical lines in the panels with the line profiles. All velocities in the figure are in units of 10^4 km s^{-1} . [The disk wind simulations are from Proga & Kallman (2004) while the intensity maps and line profiles from Rodríguez-Hidalgo et al. (in preparation)].

absorption features for the inclination angles at which strong absorption lines form (e.g., Schurch et al. 2009; Sim et al. 2010). This trend is consistent with the observational finding that BAL quasars are under-luminous in X-rays compared to their non-BAL counterparts (e.g., Brandt et al. 2000; Gallagher et al. 2007; Giustini et al. 2008).

However, these spectral features should vary in time because they are computed based on the time-dependent wind solutions. To illustrate this point, Sim et al. (2010) presented results from Monte Carlo simulations of the wind photoionization structure and of the spectra for two snap shots. In the right column of Figure 1, we show more examples of this behavior, namely synthetic line profiles of a representative UV resonance line, C IV 1549 Å for a fixed inclination angle of 75° but at various times.

The synthetic line profiles indeed change with time but not necessarily in a fashion one would expect based on just following the variability of the density and velocity distributions. In particular, the wind structure is very dynamical at small radii from where the wind is launched and the failed wind that shields the outer wind develops (the third flow component in the simulations that we mentioned above). One could expect that this inner part of the flow will produce structured absorption changing on relatively short time scales, of order of days and weeks. However, the predicted line profiles show that the absorption at small velocities is relatively stable and strong. The most dramatic evolution in the line profiles occurs at very large velocities that correspond to the emergence of very fast mass ejections from relatively large distances, where the gas is well shielded from the X-ray radiation.

To better understand how and where the line absorption takes place, the second, third, and fourth columns of Figure 1 present maps of disk intensity corrected for absorption by C IV 1549 Å in the wind [see eq. 3 in Proga et al. (2002), albeit with a zeroed source function, as here we do not model emission]. The maps were computed using the same data that was used to compute the line profile. In particular, each disk annulus is assumed to radiate as a black body, with the temperature determined by the BH mass, the accretion rate, and the annulus distance from the BH. This disk intensity is then modified by the effects of transmission through the wind: for a given ray originating a given place on the disk, we used the wind solution to look for the resonance points in the wind where the C IV 1549 Å absorption occurs at a specific velocity corresponding to a specific wavelength of continuum emission from the disk [see Proga et al. (2002) for more details]. We picked three representative velocities: 0, 7.5, and 20×10^3 km s⁻¹.

The intensity maps illustrate several important effects that are of general relevance for the interpretation of observed line profiles. In particular, the wind covering factor is partial, spatially inhomogeneous, and velocity and time dependent. These effects introduce complications in inferring the wind optical depth, density and other properties based on observations. The significance of the effects has been realized by some who model observed spectra (e.g., Barlow et al. 1997; Arav et al. 1999; de Kool et al. 2002; Arav et al. 2008). Thus, our results support the idea that one should use allow for partial, inhomogeneous, velocity dependent wind covering factors while fitting or modelling observed line profiles. Another related effect is that the intensity maps show no symmetry even though the disk and its wind are axisymmetric. This effect is due to projection and the wind kinematics, i.e., its rotation and expansion.

3. Concluding Remarks

The time-dependent, axisymmetric simulations of radiation driven disk winds have shown that the wind geometry, structure and dynamics are quite complex. In particular, the wind covering factor is partial, inhomogeneous, and velocity and time dependent. Here, we illustrated that the wind complexity predicted by the simulations can be and should be accounted for while modeling and interpreting the observed absorption lines.

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